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WHAT'S NEW IN INTENSIVE CARE

How we use critical care ultrasonography in the management of cardiogenic shock: a strategic game of chess in intensive care

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Despite recent advances in the treatment of cardiogenic shock (CS), mortality remains very high. Timely diagnosis and appropriate management are critical for improving outcomes [1], considering also that the epidemiological changes in the etiology of CS. Indeed, there is a gradual reduction of CS cases due to myocardial ischemia with a parallel surge of acutely decompensated heart failure [2]. Meanwhile, the achievement of a consensus definition for CS has facilitated clinical and scientific discussions [3], and critical care ultrasonography (CCUS) has an important role for diagnosis and management of CS patients [4]. In describing our approach to the diagnosis and management of CS using CCUS, we imagined our description as a strategic game of chess, where each move should be performed in a tactical teamwork. We guide readers through the advantages and the limitations of the CCUS methods (chess pieces), with specific referral to the CS setting, where the patient represents the "*king*" to be defended (Fig. 1).

The queen: "critical care echocardiography"

Critical care echocardiography (CCE) is indicated to confirm the diagnosis of CS and establish indications and timing of acute interventions [5]. Therefore, CCE is indispensable for avoiding delays in appropriate management, guide the choice in therapies, describe hemodynamic profiles, and assess responses to interventions. [6]. Considering its pivotal role and the flexibility of her moves, CCE stands as our "*queen*" in the tactical management of CS [7, 8]. Much like the queen plays a pivotal role in most opening strategies in chess, early use of basic CCE might rule in or out a cardiac cause of shock with a very high diagnostic performance [9]. The exceptional control of the board by queen is further exemplified by advanced CCE. Using different Doppler modalities and strain imaging, advanced echocardiography can yield a comprehensive diagnosis and an in-depth hemodynamic assessment, hinting at underlying pathology, characterizing acute features vs deterioration of a chronic condition, identifying left and/or right ventricular dysfunction (LV and RV, respectively), associated valvular or pericardial diseases, and mixed causes of shock. Once CS is confirmed, CCE guides etiology-based treatment which should begin immediately. For example, assessing mitral valve complications from acute myocardial infarction informs decisions on coronary revascularization or surgery, while evaluating cardiac dysfunction in myocarditis influences decisions such as transfer to advanced care centers. Moreover, CCE is useful for providing information regarding the suitability for extracorporeal mechanical support, excluding contraindications, such as aortic regurgitation, thrombi, and patent foramen ovale. In this regard, CCE in multidisciplinary collaboration is analogous to the key role of the queen in coordinating attacks with other pieces. The queen is also key in defensive strategies in avoiding attacks by the opponents. CCE aids the identification of patients with early mechanical complications. Ventricular septal, free wall and papillary muscle ruptures are typically diagnosed by CCE and current guidelines recommend that mechanical complications should be treated as early as possible after

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Fig. 1 The "chessboard" of critical care ultrasonography and monitoring with the armamentarium at disposition of intensive care physicians for the management of cardiogenic shock (CS) patients. *AI* artificial intelligence, *CCE* critical care echocardiography, *CO* cardiac output, *FR* fluid responsiveness, *LVFP* left ventricular filling pressure, *LUS* lung ultrasound, *MCS* mechanical circulatory support, *PAC* pulmonary artery catheter, *PAP* pulmonary artery pressure

multidisciplinary discussion [5]. Repeated CCE exams guide our further hemodynamic management, with a focus on LV and RV dysfunction, pulmonary artery and LV filling pressures, cardiac output (CO), but also excluding pleural and pericardial effusions, and dynamic LV outflow tract obstruction. Such information impacts the choice and the dose of fluids, vasoactive and inotropic drugs. Although patients with CS uncommonly require fluid administration, a comprehensive CCE allows the assessment of fluid responsiveness and monitoring its change over time, especially in the presence of associated pulmonary edema.

Apart from the prominent role of CCE, CCUS embraces several other useful modalities (chess pieces) enhancing the assessment of CS patients. Indeed, arterial hypoperfusion characterizes the most severe CS cases, but the versatility of CCUS enables also a more comprehensive evaluation by means of lung ultrasound (LUS) and the evaluation of venous congestion as compared with restrictive venous physiology, complementing the initial appraisal of shock severity provided by CCE, whose role remains *"sovereign"*.

The bishop: "lung ultrasound"

In the strategic game of managing CS, lung ultrasound (LUS) functions much like the bishop in chess—subtle yet powerful. LUS aids CCE in clinical management, being highly accurate in differentiating between dyspnea from cardiac and non-cardiac origin, quantifying the degree of pulmonary congestion due to LV dysfunction, key elements that often escape standard monitoring tools. The assessment of the presence of pulmonary edema as well as the severity and quantification of pleural effusions can be performed in minutes with LUS, and they are highly reproducible at the bedspace [10, 11]. However, the application of LUS at the bedspace is still burdened by inconsistencies, among others due to the absence of a standardized scoring systems and the variability in LUS scanning protocols. Nonetheless, in patients presenting with shock, coupling the B line patterns on LUS with CCE parameters suggesting increased LV filling pressure (i.e., E/e' and E/A ratio) corroborates the diagnosis of CS with associated cardiogenic pulmonary edema, guiding management with vasoactive agents, ventilatory and diuretic therapy [12]. Machado et al. found a combination of LUS and echocardiography-obtained stroke volume performed within 24 h of admission in ST-elevation myocardial infarction had excellent predictive value for in-hospital mortality and development of CS [13].

LUS, as the bishop in our strategic game of chess, is employed early in our management of CS; it is easy to use with rapid interpretation, highly complementing the hemodynamic work of queen and, later on, of the rook!

The rook: "invasive cardiac output monitor"

The rook, a piece of the chessboard that is often not moved early, nonetheless, becomes pivotal in the subsequent management of CS patients. With the rook, we refer to the implementation of invasive continuous CO monitoring as part of a multimodal hemodynamic evaluation for managing complex and unstable patients. Although invasive CO monitoring is not the first-line approach (i.e., not immediately mobilized in the chessboard), it represents an essential chess piece for strategic CS management. Similar to rook in chess, bringing power when used correctly, invasive monitors offer decisive data that may shift the entire management strategy. Different options may be considered in this regard, with each center using its own method(s), which may include pulmonary artery catheterization (PAC) or transpulmonary thermodilution. Several observational studies and meta-analysis suggest that PAC use may decrease mortality in CS [14–16] although confirmation from the ongoing PACCS trial is awaited (NCT05485376). Although the use of the PAC has decreased significantly, PAC is currently recommended in patients who failed to improve to initial therapeutic interventions or where diagnostic/therapeutic uncertainty remains. If CCE is the queen in the management of CS, PAC could be her favorite rook in the strategy. If PAC is not available, centers may use other rooks, each of them with own advantages and limitations [12]. Among others, the transpulmonary thermodilution could help quantify the degree of alveolar edema by measuring extravascular lung water and assessing its likely genesis using the pulmonary vascular permeability index. However, for all "rooks", thermodilution-based measurement, which relies on detecting temperature changes distal to a cold injectate site, can be unreliable in conditions frequently

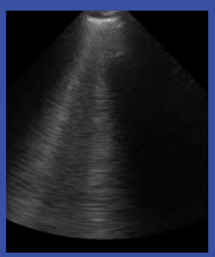
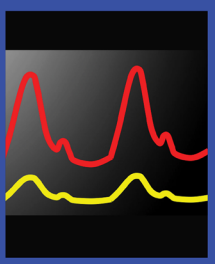
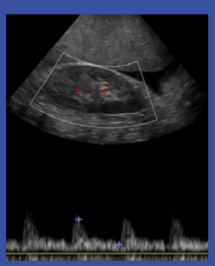
CHESS PIECE	MONITORING TOOLS	USEFULNESS IN CARDIOGENIC SHOCK LIMITATIONS IN CARDIOGENIC SHOCK
		CCE is first-line imaging modality for diagnosis of CS; Preferred modality to assess for complications (i.e. valve dysfunction); Unique for monitoring response to therapy; Essential for escalation to MCS, Cath-lab or cardiac surgery; Estimation of LVFP; Assessment of interventricular and heart-lung interaction
		Monitoring is not continuous; Filling pressures are estimated; Advanced CCE is not always available; Education in CCE is currently a challenge
		LUS permits the rapid identification and quantification of pulmonary edema; Monitoring response to therapy; Complements the CCE in assessing LVFP
		It is not diagnostic for the etiology of CS; does not address the genesis of pulmonary edema
		*Pulse contour analysis:* Allows continuous blood pressure monitoring; can track CO changes in response to interventions; may be used to test FR
		PAC: Gold standard for measuring CO; allows direct measurement of PAP and LVFP; differentiates pre- and post-capillary pulmonary hypertension
		Both: not diagnostic of CS etiology of shock; Not feasible as first-line approach; Variations in use among centers *PAC:* requires greater knowledge and practice; proficiency and utilization have decreased over the years.; intermittent CO monitoring (most cases), unable to assess FR
		Venous congestion allows to identify congestive phenotypes; Quantification of maladaptive consequences of congestion; Monitoring of decongestion in case of off-loading strategy
		Validation studies still lacking; Not established role in general intensive care; Low inter-rater reproducibility; Difficult to master
		Telemedicine and AI might allow provision of distant support in remote centers with image transfer and case discussion; Identification of phenotypes and early prognostication
		Not yet established role; Sensible data sharing; Need of adequate data quality.

Fig. 1 (See legend on previous page.)

seen in CS, such as low flow states, intracardiac shunts, and tricuspid regurgitation.

The knight: "venous congestion assessment"

Maladaptive consequences of arterial hypoperfusion perpetuate shock and multiorgan failure, with associated very high mortality. Just as the knight can leap over pieces and expose hidden threats on the board, assessment of arterial resistive index in renal and splenic circulation, combined with venous congestion using Venous Excess Ultrasound, might provide an assessment of the hemodynamic phenotype that may go unnoticed with standard monitoring tools. Additionally, evaluating arterial and venous waveforms across multiple organ systems can help distinguish the underlying cause of organ hypoperfusion in CS. Combined Doppler evaluation of these organs can help distinguish between etiologies: ischemic-related shock might show high renal resistive index (RRI) with low venous pulsatility, indicating primary arterial hypoperfusion, while in acute decompensation of heart failure, high RRI is most likely associated with marked venous pulsatility, reflecting a significant impact on hypoperfusion by venous congestion [17]. Notably, there is currently enthusiasm for the Doppler ultrasound of arterial and venous system [18], a modality mostly studied in the setting of cardiac surgery, with large knowledge gaps remaining for the general intensive care setting. Unfortunately, it is still unclear how to integrate the information gathered on resistive indices and congestion to promote a holistic CCUS approach to the patient with CS. Similar to knight piece on the chessboard, interpretation of these flow patterns is not straightforward, demands greater skills to master it, although it might guide management in a powerful way when used adequately.

Assembling the major pieces in CCUS

Therefore, CCE and LUS allow the evaluation of the efficacy and tolerance of therapeutic interventions, taking into account the ventilatory settings and all the pharmacological interventions implemented. Some examples are provided. Positive pressure ventilation will decrease the myocardial transmural pressure by decreasing LV afterload. At the same time, increased intrathoracic pressures will increase RV afterload, so positive pressure ventilation works a double-edged sword that has to be carefully considered. In this regard, CCE represents the ideal instrument for serially assessing heart–lung interactions. From pharmacological perspectives, noradrenaline is the first-line vasopressor recommended to restore blood pressure in the presence of persistent arterial hypoperfusion in CS patients; in these patients, CCUS may complement the results of CCE. Short-term inotrope therapy is recommended to increase CO only when there is evidence of arterial hypoperfusion despite adequate filling status [5]. CCE can assess the response to inotropes (present or absent) and its magnitude (dose–effect), including any potential deleterious effects such as LV outflow tract obstruction. Advanced hemodynamic parameters obtained with serial CCE examinations and the PAC can help with choice of these agents, titration, and their weaning [19]. CCE can provide information on how stroke volume is generated (including loading conditions, contractility, cardiac remodeling, valvular insufficiency), while the PAC provides direct information on LV filling pressures and allows the differentiation between pre- and post-capillary pulmonary hypertension. In addition to the assessment of arterial hypoperfusion, venous Doppler ultrasound provides additional information for evaluating organ perfusion [17].

The pawns

Information collected with CCUS (including CCE) integrated with other hemodynamic monitors and clinical variables may provide a means for identifying prognostically important endotypes that may respond differently to management strategies. CCE is useful for the early identification of clinical deterioration, distinguishing patients requiring prompt escalation of management (i.e., with extracorporeal membrane oxygenation or micro-axial flow pump or proceeding to surgery) from those that are unlikely to be salvageable.

Education in CCUS and in CCE is an important issue that contributes to the disparities in treatment of CS. Many centers lack access not only to drugs and mechanical assistance, but also to educational programs in advanced CCE (and CCUS) [20]. In this regard, a possible improvement in the care of these patients may be provided by networking and telemedicine, which should include information collected by all the CCUS items and shared with experts. Indeed, the availability of CCUS differs from center to center, and the possibility of online consultations with an experienced team might provide useful support for remote and/or less equipped centers. Moreover, the use of artificial intelligence for interpreting large datasets of high-quality CCUS and hemodynamic data may help in the prediction of clinical deterioration and the identification of relevant endotypes for individualized treatment strategies. Hence, telemedicine and the use of artificial intelligence (with its multiple possibilities) may currently hold a minority role in the strategy of the chess game, representing the pawns aiding the role of CCUS and CCE, quietly enabling progress, supporting more powerful pieces, and even

transforming into a queen with continuous advancement ultimately completing the chessboard!

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Declarations

Conflicts of interest
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